

Too much *pasta* for pulsars to spin down.

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Abstract

The lack of X-ray pulsars with spin periods > 12 s raises the question about where the population of evolved high magnetic field neutron stars has gone. Unlike canonical radio-pulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10-20 s. This high resistivity is one of the expected properties of the *nuclear pasta phase*, a proposed state of matter having nucleons arranged in a variety of complex shapes. Our findings suggest that the maximum period of isolated X-ray pulsars can be the first observational evidence of the existence of such phase, which properties can be constrained by future X-ray timing missions combined with more detailed models.

It has long been hoped that stringent constraints could be placed on the equation of state of dense matter from astrophysical measurements of neutron stars, the compact remnants of the explosion of massive stars. Up to the present time, however, despite important breakthrough discoveries [1, 2, 3] we still fall short (see e.g. [4] for a recent review). The majority of neutron stars are observed as radio-pulsars with magnetic fields in the $\sim 10^{11} - 10^{13}$ G range, that spin down due to magneto-dipole radiation losses, while converting a fraction of their rotational energy into electromagnetic radiation. The traditional wisdom that, when the star is not accreting matter from a companion star in a binary system, its main energy source comes from rotational energy, was shattered with the discovery of the so-called *magnetars*, a class that includes anomalous X-ray pulsars and soft gamma-ray repeaters (SGRs) [5]. At present, there are over twenty of these (mostly young) neutron stars characterized by high X-ray quiescent luminosities (generally larger than their entire reservoir of rotational energy), short X-ray bursts [6], sometimes displaying giant flares [7], and/or transient pulsed radio emission [8].

In the most successful model [9], magnetars are believed to be endowed with large magnetic fields, $B \sim 10^{14} - 10^{15}$ G, which explains their large periods (2 – 12 s), compared to those of normal isolated radio-pulsars (mostly in the range 0.1 – 1 s). Relatively high fields are also observed in a class of nearby thermally emitting neutron stars usually known as *the magnificent seven*. These are objects with magnetic fields of $\sim 10^{13}$ G, intermediate between magnetars and radio-pulsars, but their periods also cluster in the same range as for magnetars. Although there are hints pointing to an evolutionary link between magnetars, nearby isolated X-ray pulsars, and some high-B radio-pulsars, a complete "grand unification theory" is still lacking [10]. Interestingly, some sources (e.g. 1E 1841–045, SGR 0526–66, SGR 1806–20 among others) are known to be young and they already have periods from 7 to 12 s. With their current estimated dipolar fields, they should easily reach periods of 20 or 30 s in a few thousand more years. This seems in contradiction with a steady pulsar spin down rate. Where is the population of evolved

high magnetic field neutron stars with long periods? Why none of the middle age magnetars, or the older X-ray pulsars have longer periods?

For rotation-powered radio-pulsars, the strong dependence of the radio luminosity and the beaming angle with the rotation period, and the selection effect of several radio surveys for long spin periods, result in the lack of observed radio pulsars with periods longer than a few seconds. For X-ray pulsars, however, there is no reason to expect any selection effect. We plot in Figure 1 the spin period distribution of isolated X-ray pulsars and X-ray binary pulsars, showing that there are no observational limitations to the detection of slow periods in X-ray binaries. When other torques are present (accretion), X-ray pulsars with rotation periods of hundreds or even thousand of seconds are clearly observed. The fact that no X-ray emitting isolated neutron star has been discovered so far with a period $> 12\text{s}$ must therefore be a consequence of a real physical limit and not simply a statistical fluctuation [14]. The easiest and long-standing answer is that the magnetic field decays as the neutron star gets older [15] in such a way that its spin-down rate becomes too slow to lead to longer rotation periods during the time it is still bright enough to be visible as an X-ray pulsar. In this scenario, *low-field magnetars* [11] are simply old magnetars whose external dipolar magnetic field has decayed to normal values [12, 13]. However, no detailed quantitative predictions supported by realistic simulations have been able to reproduce the observational limits. This is the purpose of this work.

The long-term life in the interior of a neutron star is very dynamic. As the star cools down, the internal magnetic field is subject to a continuous evolution through the processes of Ohmic dissipation, ambipolar diffusion, and Hall drift [16, 17]. Soon after birth (from hours to days, at most) protons in the liquid core undergo a transition to a superconducting phase and a solid crust is formed. The neutron star crust (see [18] for a comprehensive review) is for the most part an elastic solid, comprising a Coulomb lattice of *normal* spherical nuclei. It is only about 1 km thick (10% of the star radius) and contains 1% of its mass, however it is expected to play

a key role in various observed astrophysical phenomena (pulsar glitches [19], quasi-periodic oscillations in SGRs [20], thermal relaxation in soft X-ray transients [21], etc.) Among all the ingredients that determine the magneto-rotational evolution of a neutron star, one key issue is the magnetic diffusivity in the region where currents are placed. If currents supporting the magnetic field of neutron stars are predominantly in the core, the extremely high conductivity would result in little field dissipation, thus keeping a nearly constant magnetic field during the first Myr of a pulsar life. On the contrary, a magnetic field supported by currents in the crust is expected to appreciably decay in ≈ 1 Myr, because the combined action of Ohmic dissipation and the Hall drift displaces currents toward the inner crust [22, 23]. Therefore, the inner crust is actually the most important region to determine the magnetic field dissipation timescale.

The inner crust is also where the *nuclear pasta*, a novel state of matter having nucleons arranged in a variety of complex shapes, is expected to appear. In the innermost layers near the crust/core boundary, because of the large effect of the Coulomb lattice energy, cylindrical and planar geometries can occur, both as nuclei and as bubbles [24]. These phases are collectively named nuclear pasta (by analogy to the shape of spaghetti, macaroni and lasagna). More sophisticated molecular dynamics simulations [25, 26] have shown that it may be unrealistic to predict the exact sizes and shapes of the pasta clusters, and that the actual shape of the pasta phase can be very amorphous, with a very irregular distribution of charge. This is expected to have a strong impact on the transport properties, in particular on the electrical resistivity, because electron scattering off crystal impurities becomes the dominant process when the star has cooled down enough (typically, $\sim 10^5$ yr). The relevant nuclear parameters that determine the thickness of the crust and the range of densities at which pasta might appear are the symmetry energy and its density dependence close to nuclear saturation density. This important parameters also determine global properties such as the radius and moment of inertia, and have been proposed to have a potential observational effect in the crust oscillation frequencies [27, 28].

In the absence of a more detailed microscopical calculation, we can use the impurity parameter formalism as a first simplified approximation to the complex calculation of the resistivity. The impurity parameter, Q_{imp} , is a measure of the distribution of the nuclide charge numbers in the crust material, and it tells how “crystalline” ($Q_{imp} \ll 1$) or “amorphous” ($Q_{imp} \gg 1$) is the neutron star crust. A pasta region, by definition, is expected to have a large Q_{imp} since it is expected that clustering happens in a very irregular manner. We also note that the conductivity of an amorphous crust calculated with molecular dynamics simulations is even lower by an order of magnitude than the estimates obtained using the impurity parameter formalism (as shown in [29] for the outer crust in the scenario of accreting neutron stars). The “effective” Q_{imp} to be used in the impurity parameter formalism must then be high to reproduce the molecular dynamics results. We will set $Q_{imp} = 0.1$ in the outer crust but, to explore the sensitivity of our results to this important parameter in the pasta region ($\rho > 6 \times 10^{13} \text{ g/cm}^3$), we will let it vary between $Q_{imp} = 1 - 100$. We now discuss our findings about the observational imprint of *nuclear pasta* in the long term evolution of neutron stars.

As initial model, we have chosen a neutron star born with an initial dipolar field of $B = 3 \times 10^{14} \text{ G}$ (at the pole). We refer to section 2 in [30], section 4 of [31], and references therein, for all details about the magnetic field geometry, the equation of state employed and other microphysical inputs. The evolution is followed for 10^6 years using the new 2D code developed by [23], to which we refer for technical details. We consider five models, with three different masses and Q_{imp} in the pasta phase (see table 1). In Fig. 2 we show the value of the magnetic field at the pole as a function of age for the different models. During the first $\sim 10^5 \text{ yr}$, the field is dissipated by a factor ~ 2 for all the models, with slight differences due to the different neutron star masses, and ΔR_{crust} . In this regime, the neutron star crust is still warm and electron scattering off impurities is not the dominant process to determine the electrical conductivity. Thereafter, as the star cools, the evolution strongly depends on the impurity parameter in the

inner crust. For low values of Q_{imp} (model E), the field almost stops to dissipate and remains high, with some oscillations due to the Hall term in the induction equation [22, 23]. By contrast, a large value of Q_{imp} (models A, B, C) results in the dissipation of the magnetic field by one or even two orders of magnitude between 0.1 and 1 Myr. Differences in the time evolution of the magnetic field have a clear observational effect that we discuss now.

The spin-down behavior of a rotating neutron star is governed by the energy balance equation relating the loss of rotational energy to the energy loss rate \dot{E} , given by magneto-dipole radiation, wind, gravitational radiation, or other mechanisms. The most accurate calculations of the spin-down luminosity of an oblique rotator [32] can be well approximated by

$$\dot{E} = \frac{B_p^2 R^6 \Omega^4}{4c^3} (1 + \sin^2 \alpha), \quad (1)$$

where R denotes the neutron star radius, $\Omega = 2\pi/P$ is the angular velocity, α is the angle between the rotational and the magnetic axis, and c is the speed of light. The energy balance equation between radiation and rotational energy losses gives

$$I\Omega\dot{\Omega} = \frac{B_p^2 R^6 \Omega^4}{4c^3} (1 + \sin^2 \alpha) \quad (2)$$

where I is the effective moment of inertia of the star.

Numerically integrating equation (2) with $B_p(t)$ obtained from our simulations, we can obtain evolutionary tracks in the $P - \dot{P}$ diagram, which allows a close comparison to observed timing properties of X-ray pulsars. This is shown in Fig. 3, where we compare the theoretical trajectories of a neutron star up to an age of 5 Myr to the sample of isolated X-ray pulsars with the largest rotation periods. The most important qualitative difference is that for models A, B, C (high Q_{imp}) the evolution tracks become vertical after $\sim 10^5$ yr, indicating that the period has reached an asymptotic value while its derivative steadily decreases. The particular upper limit of P depends on the neutron star mass, the initial field and the value of Q_{imp} , but this gives a natural explanation to the observed upper limit to the rotation period of isolated X-ray

pulsars, and the observed distribution with objects of different classes clustering in the range $P = 2 - 12$ seconds while \dot{P} varies over six orders of magnitude. Conversely, in models D and E (low or moderate impurity in the pasta region) the period keeps increasing due to the slower dissipation of the magnetic field, which in principle predicts that pulsars of longer periods (20-100 s) should be visible. In models D and E, the slow release of magnetic energy through Joule heating keeps the neutron star bright and visible much longer than for models A, B and C. The luminosity of models D and E, at an age of a few Myrs, is $\approx 10^{32}$ erg/s, high enough for sources a few kpc away to be detectable with present X-ray instruments.

Other possible torque mechanisms, that would enter as extra-terms in equation (2), such as stellar wind or accretion from a fallback disk, could act only in the early stages of a neutron star life and may contribute to explain the observed large values of \dot{P} in some objects. Furthermore, the effective moment of inertia I , may also vary with time as the superfluid part of the core grows during the first hundreds of years. A simple phenomenological model for the rotational evolution of the normal and superfluid components and its observational effects have been discussed in [33]. Note, however, that the main conclusion of our calculations is not affected: if a pasta phase is present with a highly irregular charge distribution in nuclear clusters, evolutionary tracks in the $P - \dot{P}$ diagram will bend down after 10^5 yrs regardless of the particular model. As a consequence, there will be a maximum spin period for isolated X-ray pulsars. We must also note that there is some dependence on other microphysical inputs, in particular the superfluid gaps, but a very high impurity parameter in the inner crust is needed to explain a maximum period of about 12 s. Under these conditions, the resistivity is almost independent of temperature, so the effect of varying the superfluid gap (or other parameters that modify the local temperature) is negligible.

We conclude that there is a direct correlation between the maximum observed spin period of isolated X-ray pulsars and the existence of a highly resistive layer in the inner crust of neutron

stars. This is a plausible evidence for the *nuclear pasta* phase near the crust/core interface. The precise density at which the pasta phase appears, the geometry of the nuclear clusters, and their charge distribution is strongly dependent on the symmetry energy of the nuclear interaction and its density dependence. Therefore, its imprint can be present in the evolution of the magnetic field, and opens the possibility of constraining this parameters using a new astrophysical observable. In particular, as present and future space missions, such as LOFT (Large Observatory For X-ray Timing [34]), keep increasing the statistics of X-ray pulsars, and realistic theoretical models are used as input for neutron star population synthesis studies, we will be able to accurately constrain the size and properties of the pasta phase in neutron stars and, therefore, the equation of state of dense matter.

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Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{imp}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1

Table 1: Summary of the properties of the five neutron star models considered in this work: mass, moment of inertia (in units of $10^{45} \text{ g cm}^{-2}$), thickness of the crust and of the pasta phase, and impurity parameter in the pasta phase.

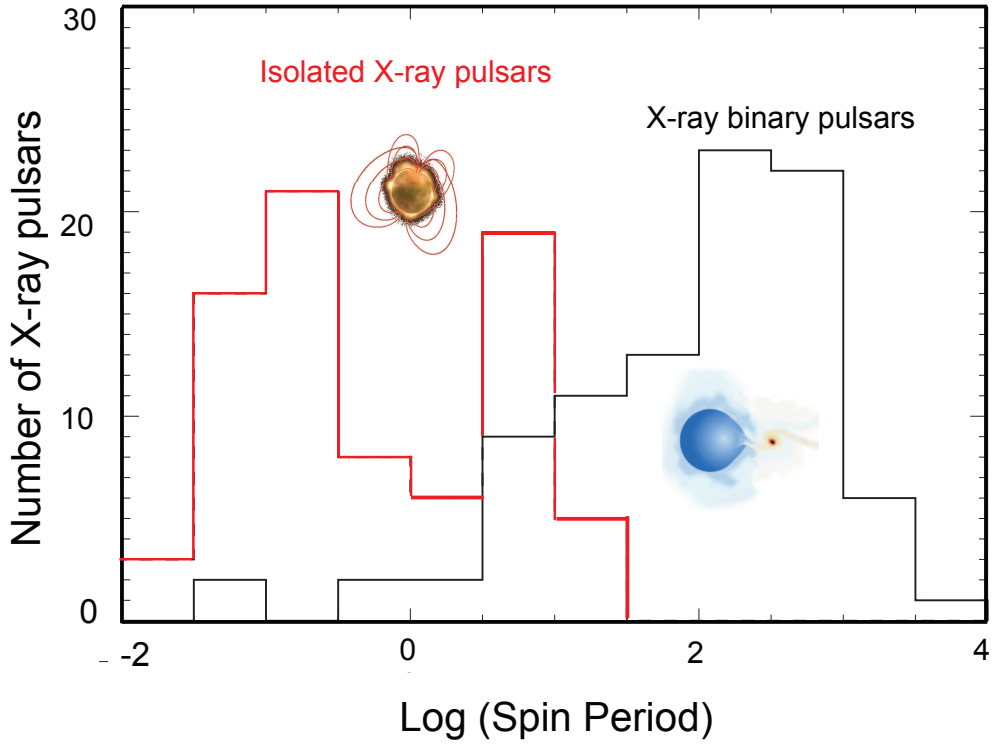


Figure 1: Period distribution of isolated neutron stars (red) and neutron stars in binary systems (black).

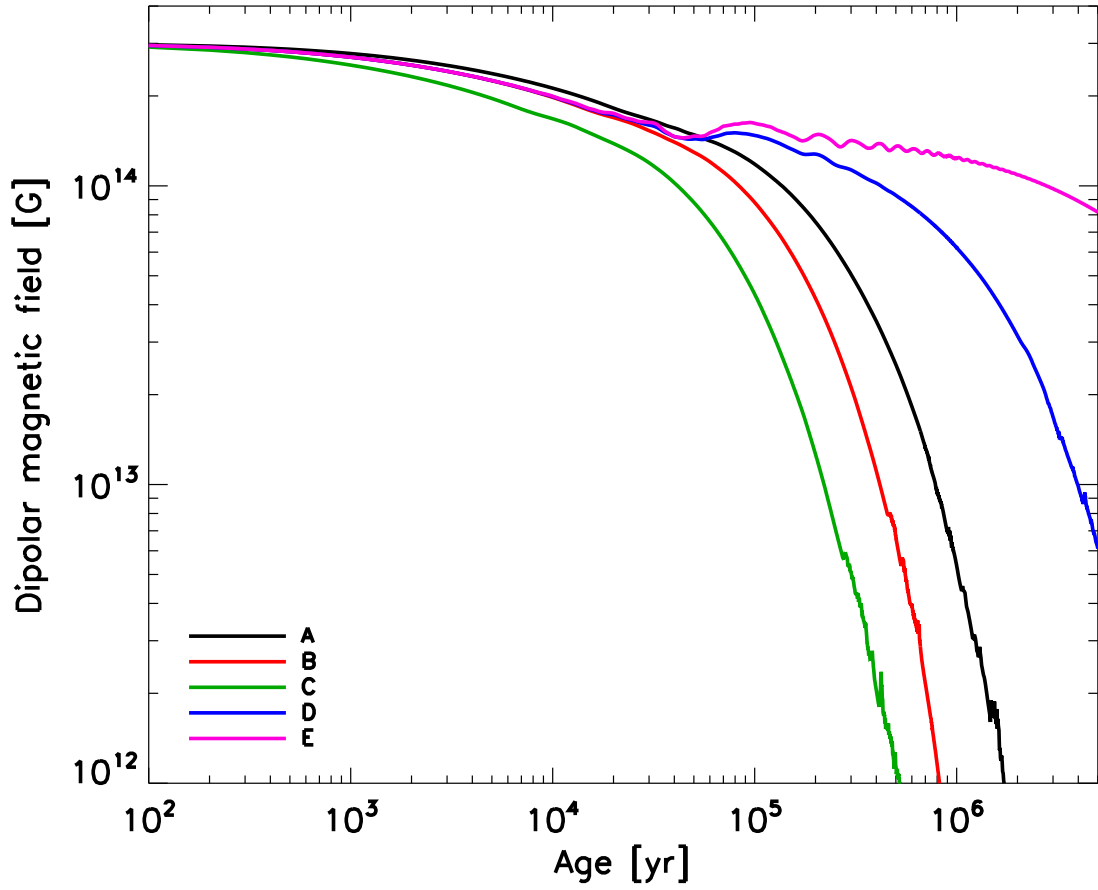


Figure 2: Magnetic field strength at the pole (B_p) as a function of the neutron star age for the models listed in Table 1.

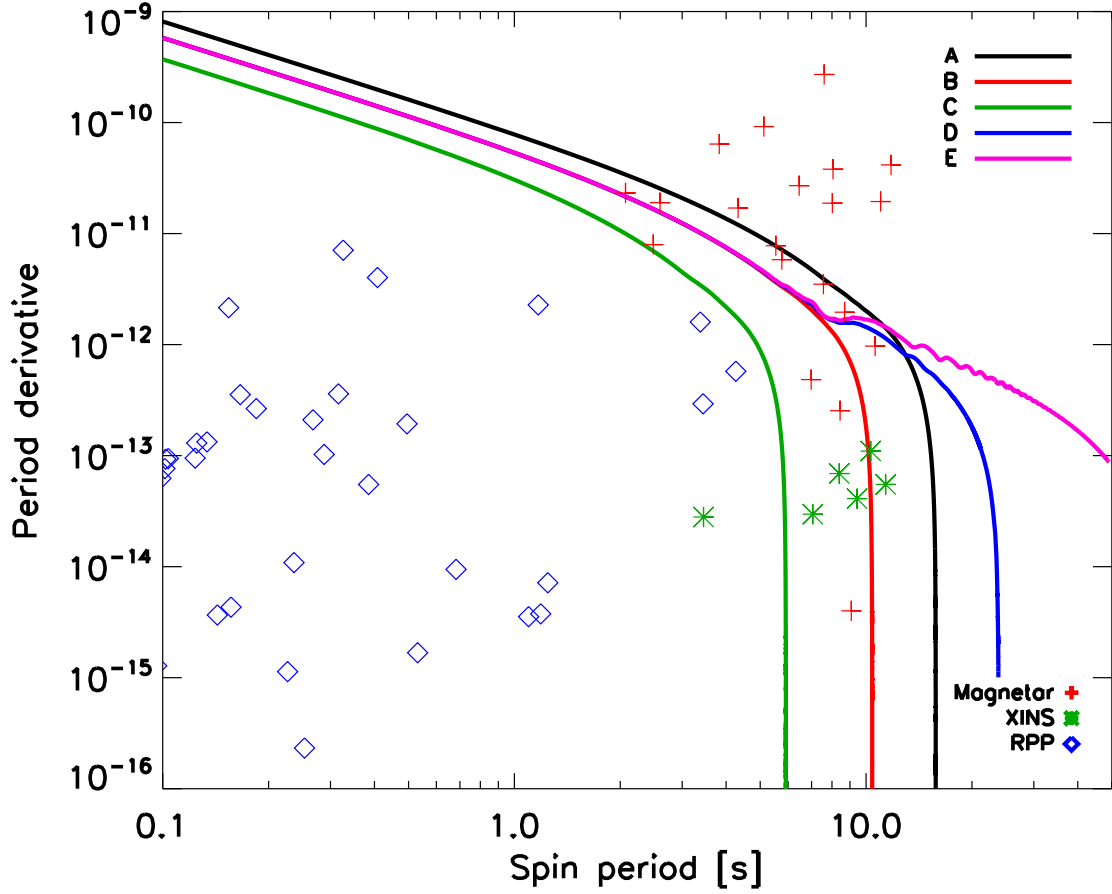


Figure 3: $P - \dot{P}$ diagram for magnetars, X-ray Isolated Neutron Stars and Rotation Powered Pulsars with X-ray emission. We overplot evolutionary tracks up to 5 Myr for the five models listed in Table 1.